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Collective Josephson Plasma Resonance in the Vortex State of $Bi_2Sr_2CaCu_2O_{8+\delta}$

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We have measured the microwave surface resistance (30–60 GHz) for different crystallographic orientations in the vortex state of $Bi_2Sr_2CaCu_2O_{8+\delta}$. A sharp magnetoabsorption resonance is observed below T_c when ac electric fields and magnetic fields are applied parallel to the c axis ($\boldsymbol{E}_{ac} \parallel \boldsymbol{B} \parallel c$). We argue that the observed resonance arises from collective Josephson plasma oscillations generated by interlayer Josephson currents. From the frequency and temperature dependence of the resonance, we discuss the interlayer phase coherence in the vortex liquid and solid states quantitatively.

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In highly anisotropic superconductors, the frequency of the plasma perpendicular to the conduction planes is very low. In high-T_c cuprates, plasma mode with polarization perpendicular to CuO_2 planes ($\boldsymbol{E} \parallel c$) lies well below the superconducting gap due to the strong anisotropy and the large gap energy. Consequently, plasma damping processes such as Landau damping and optical phonon damping are prohibited to occur in the superconducting state of high-T_c cuprates [1]. Related to this low lying and stable plasma mode, many exotic electromagnetic phenomena that have never been observed in any other superconductors are predicted to occur [1,2]. For example, the appearance of a sharp plasma edge with c-axis polarization arising from superconducting carriers has been reported below T_c in the frequency range of 20–50 cm^{-1} by the optical reflection measurements for $La_{2-x}Sr_xCuO_4$ [3]. On the other hand, in $Bi_2Sr_2CaCu_2O_{8+\delta}$ with extremely large anisotropy ($\lambda_c/\lambda_{ab} > 100$ with λ_c and λ_{ab} being the London penetration length for the c axis and for the ab plane), the plasma edge for $\boldsymbol{E} \parallel c$ has not been observed down to 30 cm^{-1} (900 GHz) [4]. This implies that the plasma mode is in the mm wavelength range in $Bi_2Sr_2CaCu_2O_{8+\delta}$. It is well established that $Bi_2Sr_2CaCu_2O_{8+\delta}$ behaves as stacks of superconductor-insulator-superconductor Josephson tunnel junctions [5]. In this case, the plasma oscillation is generated by Josephson supercurrents due to the quantum phase difference between adjacent superconducting layers (Josephson plasma). The Josephson plasma oscillation has been studied in low-T_c Josephson tunnel junctions [6]. In the low-T_c junctions, the Josephson plasma is confined within the insulating barrier owing to its frequency being well below the plasma cutoff frequency in the bulk superconductors. In $Bi_2Sr_2CaCu_2O_{8+\delta}$, however, the CuO_2 layers are too thin to fully screen Josephson plasma oscillations. As a result, the Josephson plasma oscillation extends over many insulating layers; i.e., the collective quantum phase oscillation of many CuO_2 layers along the c axis.

Recently, a sharp magnetoabsorption resonance has been discovered in the vortex state of $Bi_2Sr_2CaCu_2O_{8+\delta}$ when the magnetic field $\boldsymbol{B}$ is applied normal to CuO_2 planes [7]. The most peculiar feature of this resonance is that the resonance frequency decreases with increasing the magnetic field (anticyclotronic) opposite the free carrier cyclotron resonance mode. This resonance has been considered to occur in two-dimensional CuO_2 planes and hence discussed by cyclotron resonance, electronic excitation within the vortex core, low lying vortex vibration mode, and so on [7,8]. However, the mechanism of the resonance is still an open question. In this Letter, by performing the measurements of surface resistance in the vortex state of $Bi_2Sr_2CaCu_2O_{8+\delta}$ for different crystallographic orientations, we present strong evidence that this resonance represents the collective Josephson plasma excitation mode in a magnetic field. We show that the resonance is generated by an ac electric field along the c axis ($\boldsymbol{E}_{ac} \parallel c$). From the frequency and temperature dependence of the resonance, we discuss the interlayer phase coherence in the vortex liquid and solid states quantitatively.

The single crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ ($T_c = 85$ K) have been grown by the traveling-solvent-floating-zone technique. The crystal is placed in a rectangular cavity with TE_{102} mode made of copper. Most of the measurements were performed at 45 GHz. Three different configurations were employed to measure the surface resistances. In one configuration, to measure out-of-plane electronic properties, the sample is placed at the maximum $\boldsymbol{E}_{ac}$ (minimum $\boldsymbol{H}_{ac}$), and oriented such that $\boldsymbol{E}_{ac}$ is directed parallel to the c axis. The in-plane properties are measured by placing the sample in the maximum $\boldsymbol{H}_{ac}$ (minimum $\boldsymbol{E}_{ac}$) in such a way that $\boldsymbol{H}_{ac}$ is parallel to the c axis. Consequently, in this configuration, the eddy currents due to $\boldsymbol{H}_{ac}$ are flowing in the CuO_2 planes. Similarly, the in-plane properties are also measured by placing the sample in the $\boldsymbol{E}_{ac}$ maximum and oriented such that $\boldsymbol{E}_{ac}$ is perpendicular

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to the c axis. In order to obtain high sensitivity, we used the bolometric technique described in Ref. [9].

The magnetic field dependence of the surface resistance R_s for two different configurations is shown in Fig. 1. The magnetic fields ($\boldsymbol{B} \parallel c$) are swept from 7 T to -7 T through zero field. A small hysteresis at low fields is attributed to the effect of the trapped field in the crystal. Figure 1(a) shows R_s obtained from the configuration where $\boldsymbol{H}_{\mathrm{ac}}$ is parallel to the c axis ($\boldsymbol{H}_{\mathrm{ac}} \parallel \boldsymbol{B} \parallel c$). In this case, strongly B-dependent R_s is observed, which can reasonably be accounted for by the effect of vortex motion driven by eddy currents flowing CuO_2 planes. Above 0.1 T, R_s increases as $R_s \propto \sqrt{B}$. This is a typical behavior of the flux flow surface resistance [9]. A similar field dependence of R_s was observed in the configuration $\boldsymbol{E}_{\mathrm{ac}}$ perpendicular to the c axis ($\boldsymbol{E}_{\mathrm{ac}} \perp \boldsymbol{c} \parallel \boldsymbol{B}$), although it is not presented here.

The sharp magnetoabsorption peak is observed when $\boldsymbol{E}_{\mathrm{ac}}$ is directed parallel to the c axis [Fig. 1(b)]. In this configuration, note that the Lorentz-force-free condition is realized because the ac currents $\boldsymbol{J}_{\mathrm{ac}}$ flow parallel to the c axis ($\boldsymbol{B} \parallel \boldsymbol{J}_{\mathrm{ac}} \parallel c$) [10]. This is confirmed by the fact that R_s shows only little magnetic field dependence, indicating absence of flux flow dissipation. These results provide decisive evidence that *the resonance arises not from the in-plane electron motion but from the out-of-plane one* in $Bi_2Sr_2CaCu_2O_{8+\delta}$. Furthermore, to determine which component of a magnetic field causes the resonance, we tilted $\boldsymbol{B}$ from the c axis. Figure 2 shows R_s as a function of $B\cos\theta$, where θ is the angle between B and the c axis. R_s is scaled by $B\cos\theta$ well, indicating that the resonance mode reflects the two-dimensional nature of the system. Magnetic field dependence of R_s at 45 GHz at various temperatures is displayed in Fig. 3. The resonance appears below T_c. This implies that the resonance is the response of carriers condensed in the superconducting state.

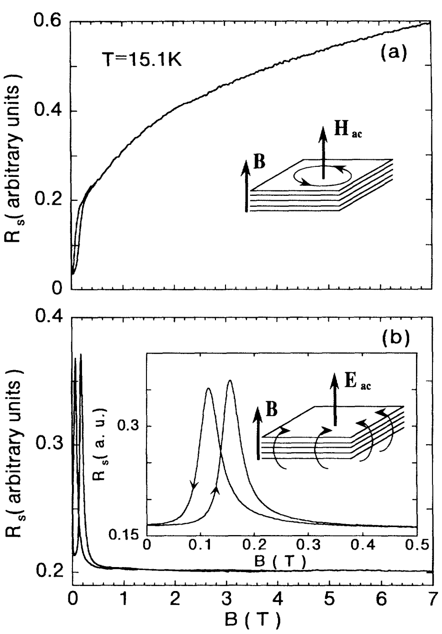

FIG. 1. The surface resistance R_s of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (sample A) at 45 GHz as a function of magnetic field at 15.1 K. External field $\boldsymbol{B}$ is applied parallel to the c axis ($\boldsymbol{B} \parallel c$). In the upper panel (a), R_s is measured with ac magnetic field $\boldsymbol{H}_{\mathrm{ac}}$ parallel to the c axis. In the lower panel (b), the same quantity is measured with ac electric field $\boldsymbol{E}_{\mathrm{ac}}$ parallel to the c axis. Resonance occurs in the configuration with $\boldsymbol{E}_{\mathrm{ac}} \parallel \boldsymbol{B} \parallel c$. The inset of (b) shows R_s at low fields.

Summarizing the salient features, the resonance is (1) the response in the superconducting state, (2) generated by $\boldsymbol{E}_{\mathrm{ac}} \parallel c$, (3) anticyclotronic [7] (cf. Fig. 5), and (4) caused by field component parallel to the c axis. These results provide strong evidence that the resonance arises from the Josephson plasma excitation in a magnetic field. When the plasma frequency ω_p $(= \sqrt{(4\pi n e^2/m^*)}^{1/2}$ with n the carrier density and m^* the effective mass along the c axis) is much smaller than the superconducting gap energy Δ (≈ 10 THz for $Bi_2Sr_2CaCu_2O_{8+\delta}$), the dielectric function $\varepsilon_c(\omega)$ for $\boldsymbol{E} \parallel c$ in the superconducting state can be expressed as

$$\varepsilon_c(\omega) = \varepsilon_0 \left[1 - \frac{\omega_{sp}^2}{\omega(\omega + i0^+)} - \frac{\omega_{np}^2}{\omega(\omega + i\Gamma)} \right], \quad (1)$$

where ε_0 is the dielectric constant of the crystal [1]. The second term in the bracket is the contribution of carrier condensed in the superconducting state with the Josephson plasma frequency ω_{sp} $(= c/\lambda_c\sqrt{\varepsilon_0})$. The third term represents the thermally excited quasiparticle contribution, where ω_{np} $(= \sqrt{4\pi n_q e^2/m^* \varepsilon_0}$ with n_q the quasiparticle density) and Γ are the plasma frequency and the scattering rate of quasiparticles, respectively. In the two-fluid model, $\omega_{sp}^2 + \omega_{np}^2$ is equal to ω_p^2/ε_0. The third term may be neglected because the quasiparticle scattering rate ($1/\Gamma \sim$ 1 psec [11]) is much larger than our microwave frequency. The Josephson plasma frequency ω_{sp} is given by

$$\omega_{sp}^2 = 8\pi^2 c d j_c^{(c)} / \varepsilon_0 \Phi_0 , \quad (2)$$

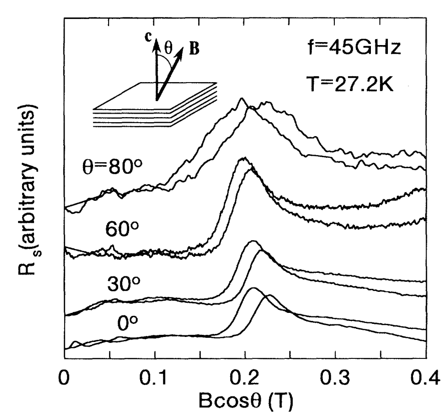

FIG. 2. Angular dependence of surface resistance R_s of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (sample A) at 27.2 K. R_s is plotted as a function of field component parallel to the c axis ($B\cos\theta$).

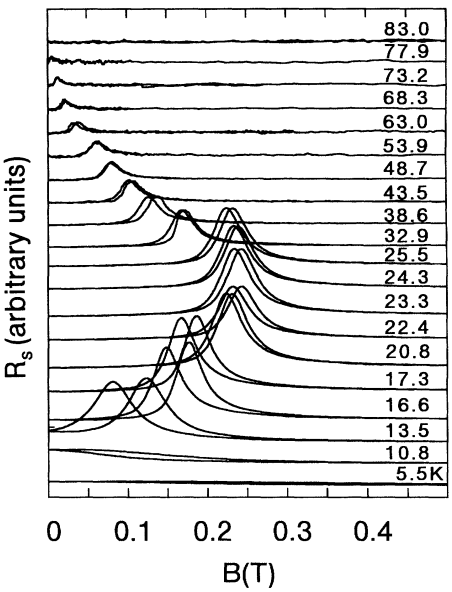

FIG. 3. The surface resistance R_s of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (sample A) at 45 GHz as a function of the magnetic field ($\boldsymbol{B} \parallel c$) at different temperatures. R_s are measured with $\boldsymbol{E}_{ac}$ parallel to the c axis.

where Φ_0, $j_c^{(c)}$, and d are the flux quantum, the interlayer critical current, and the c-axis unit cell length, respectively. From the I-V measurements in zero field $j_c^{(c)}$ is reported to lie from 10^2 up to 10^4 A/cm^2 in $Bi_2Sr_2CaCu_2O_{8+\delta}$ [12]. Assuming $\varepsilon_0 = 10$ in Eq. (2), ω_{sp} results in between 300 and 900 GHz. When the magnetic field is applied parallel to the c axis, $j_c^{(c)}$ falls sharply [10]. Therefore, ω_{sp} is expected to fall into our microwave window in the magnetic field. When ω_{sp} coincides with the microwave frequency ω, resonance occurs with vanishing $\varepsilon_c(\omega)$. *With increasing B, ω_{sp} decreases monotonically; accordingly the resonance mode is anticyclotronic.* Since the damping term can be neglected in Eq. (1), the resonance mode is expected to be very *sharp* in the present frequency range.

The observation of the Josephson plasma resonance gives the direct information of the phase coherence between CuO_2 layers, yielding very precise determination of $j_c^{(c)}$ without introducing any arbitrary voltage criterion in the I-V curve [Eq. (2)]. Therefore it provides us with a valuable way of investigating the vortex state. The nature of the magnetic phase diagram for the high-T_c cuprates has been a subject of great interest. It is settled that the vortex line lattice in the ab plane becomes liquid above the irreversibility temperature $T_{\rm irr}(B)$. Figure 4 shows the T dependence of the resonance field B_0 [13]. In the inset of Fig. 4, the integrated absorption intensity I_0 of the resonance is also shown. As the temperature is lowered, both B_0 and I_0 first increase and reach maximum around 20 K, then decrease with a distinct cusp. It was pointed out that the maximum in the B-T phase diagram may correspond to the vortex liquid-solid transition line obtained from I-V measurements [7]. To check this, we determined $T_{\rm irr}(B)$ from magnetization measurements by a SQUID magnetometer for the *same* samples used for the microwave experiments. It is found that the position of the maximum coincides exactly with $T_{\rm irr}(B)$ (Fig. 4), supporting Ref. [7]. These results indicate that the Josephson plasma is strongly influenced by the nature of the vortex state in the ab plane.

First we discuss the resonance in the vortex liquid state above $T_{\rm irr}(B)$. The nature of the liquid state has been controversial. A decoupling phase transition, where each CuO_2 plane completely loses the phase coherence along the c axis, is predicted to occur at some temperatures higher than $T_{\rm irr}(B)$ [14]. On the other hand, it is also argued that the decoupling is a continuous crossover [15]. The present experiments may shed light on this issue. If each CuO_2 plane is completely decoupled along the c axis, $j_c^{(c)}$ and hence ω_{sp} should vanish [see Eq. (2)] [2,14]. Our results of the finite ω_{sp} in Figs. 3 and 4 suggest that each CuO_2 plane has a high degree of phase coherence along the c axis even in the liquid state. Therefore, if the decoupling phase transition line exists, it should lie above the line connecting B_0 in Fig. 4. However, we note that the line connecting B_0 crosses the decoupling line determined by the I-V measurements [16]. Recently, both $j_c^{(c)}$ and ω_{sp} in Josephson coupled superconductors in the magnetic fields are predicted to be proportional to the spatial and thermal averages of the phase difference between layers n and $n+1$

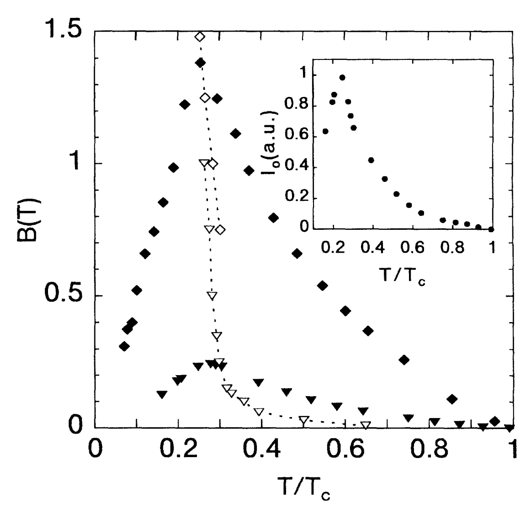

FIG. 4. Temperature dependence of the resonance fields B_0 of two $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals ($T_c = 85$ K) at 45 GHz (solid triangles, sample A; solid squares, sample B). We display only 7 T $\rightarrow$ 0 trace. The symbols (open triangles, sample A; open squares, sample B) denote the irreversibility temperature determined by magnetization measurements. The dotted lines are drawn to guide the eye. The inset shows the integrated absorption intensity of the resonance for sample A (solid circles).

$\langle \cos\varphi_{n,n+1} \rangle$ [2],

$$\omega_{sp}^2(B,T) = \omega_{sp}^2(0,T)\langle \cos\varphi_{n,n+1} \rangle,$$
$$j_c^{(c)}(B,T) = j_c^{(c)}(0,T)\langle \cos\varphi_{n,n+1} \rangle. \quad (3)$$

To see the nature of vortex decoupling quantitatively, we calculate T dependence of $\langle \cos\varphi_{n,n+1} \rangle$ at a constant B from Eq. (3). In the inset of Fig. 5 the frequency dependence of B_0 at several temperatures is shown. Below 55 K and below 1 T, $\omega_{sp}(B,T)$ depends on B as $\omega_{sp}^2(B,T) \propto B^{-\alpha}$ with $\alpha = 0.9$–1.1. Using the Ambegaokar-Baratoff model for $j_c^{(c)}(0,T)$ [17],

$$j_c^{(c)}(0,T) = \frac{\Delta(T)}{2eR_N}\tanh\left[\frac{\Delta(T)}{2k_BT}\right], \quad (4)$$

where R_N is the normal state junction resistance, the calculated T dependence of $\langle \cos\varphi_{n,n+1} \rangle$ at 1 T is displayed in Fig. 5. (We assumed $\alpha = 1$.) It is shown that $\langle \cos\varphi_{n,n+1} \rangle$ decays almost inversely proportional to T above $T_{\mathrm{irr}}(B)$. Thus it is revealed that $\langle \cos\varphi_{n,n+1} \rangle$ depends on B and T as $\langle \cos\varphi_{n,n+1} \rangle \propto B^{-\alpha}T^{-\beta}$ with $\alpha \approx 1$ and $\beta \approx 1$ in the liquid state.

Finally we discuss the resonance below $T_{\mathrm{irr}}(B)$. Although the vortex lattice in this regime has been suggested to be in a glassy state, little is known about it. Our results show that $j_c^{(c)}$ decreases rapidly with decreasing T. This behavior is opposite to the ordinary superconductors. One possible explanation is the following. In this regime, the pancake vortices are frozen forming 3D vortex lines. Randomly positioned pinning centers in CuO_2 planes cause the displacement of pancake vortices from straight lines. With increasing T, thermal fluctuation may tend to make the vortex line straight by removing vortices from the pinning center. Since $\langle \cos\varphi_{n,n+1} \rangle$ decreases with increasing the displacement of the line, $j_c^{(c)}$ is expected to increase with T.

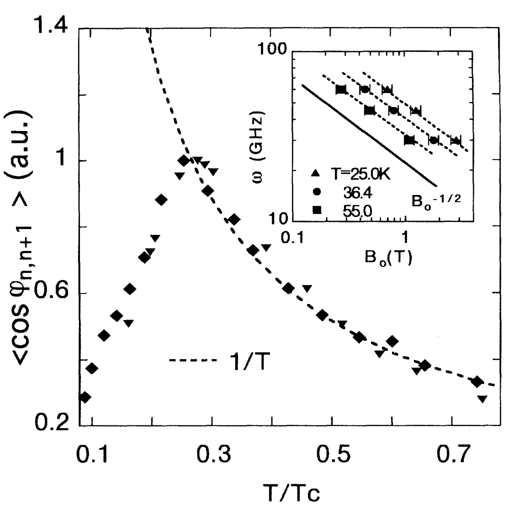

FIG. 5. Temperature dependence of the average of the phase difference $\langle \cos\varphi_{n,n+1} \rangle$ at a constant magnetic field (1 T) for two $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals (solid triangles, sample A; solid squares, sample B). For details see text. Both data are normalized by the values at the irreversibility temperatures. The broken line represents the $1/T$ curve. The inset shows the frequency dependence of the resonance fields at several temperatures. The dotted lines are a guide for the eye. The solid line shows $\omega \propto B_0^{-1/2}$.

In summary, we have performed the surface resistance measurements for different crystallographic orientations in the vortex state of $Bi_2Sr_2CaCu_2O_{8+\delta}$. We presented strong evidence that the sharp magnetoabsorption resonance observed in $Bi_2Sr_2CaCu_2O_{8+\delta}$ arises from the collective Josephson plasma excitation mode. From the frequency and temperature dependence of the resonance, we discussed the interlayer phase coherence in the vortex liquid and solid states quantitatively. The loss of the interlayer phase coherence in the vortex liquid state is shown to occur gradually without accompanying the decoupling phase transition. In the vortex solid state, the magnitude of phase coherence decreases rapidly with decreasing T.

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